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REINFORCER CONTROL AND HUMAN SIGNAL-DETECTION PERFORMANCE

VICTORIA JOHNSTONE AND BRENT ALSOP

UNIVERSITY OF OTAGO, NEW ZEALAND

Eight humans participated in a two-choice signal-detection task in which stimulus disparity was varied over four levels. Two procedures arranged asymmetrical numbers of reinforcers received for correct left- and right-key responses (the reinforcer ratio). The controlled procedure ensured that the obtained reinforcer ratio remained constant over changes in stimulus disparity, irrespective of subjects' performances. In the uncontrolled procedure, the asymmetrical reinforcer ratio could covary with subjects' performances. The receiver operating charateristic (ROC) patterns obtained from the controlled procedure approximated isobias functions predicted by criterion location measures of bias. The uncontrolled procedure produced variable ROC patterns that were somewhat like the isobias predictions made by likelihood ratio measures of bias; however, the obtained reinforcer ratio became more extreme as discriminability decreased. The obtained pattern of bias was directly related to the obtained reinforcer ratio. This research indicates that criterion location measures seem to be preferable indices of response bias.

Key words: signal detection, reinforcer ratio, signal presentation ratio, discriminability, response bias, key press, humans

In a two-choice detection task, subjects are presented with one of two possible stimuli, S_1 or S_2. Typically, the stimuli are defined by the presence or absence of a particular stimulus, or they vary along a dimension such as color or light intensity. Subjects then choose between two concurrently available responses such as a left-key press and a right-key press (B_1 and B_2). B_1 responses on S_1 trials and B_2 responses on S_2 trials are defined as correct, and are conventionally labeled as hits and correct rejections, respectively. B_2 responses on S_1 trials and B_1 responses on S_2 trials are defined as incorrect and are conventionally labeled as misses and false alarms, respectively. Subjects sometimes receive feedback for their correct and incorrect responses. Models of detection seek to describe choice behavior in such tasks as a function of two independent processes. They measure subjects' discrimination between stimuli (their tendency to respond B_1 when S_1 is presented and B_2 when S_2 is presented). They also measure subjects' tendency to favor one type of response over another, known as response bias.

Traditional models of detection evolved from investigations into human psychophysical judgments (e.g., signal-detection theory, Green & Swets, 1966; choice theory, Luce, 1963). Investigations into human detection performance are generally grounded in this psychophysical framework, and tend to concentrate on the factors that influence discriminability rather than those that influence response bias. The control of response bias in humans is less well understood and is the focus of the current paper.

The psychophysical formulation of signal detection assumes that repeated presentations of the S_1 and S_2 stimuli result in two overlapping normal distributions. Subjects solve the detection task by selecting a level of sensory activity above which they respond B_1 and below which they respond B_2. Bias from this perspective depends on a subject's tendency to identify a particular level of sensory activity the result of an S_1 or S_2 presentation. Numerous response bias measures have been proposed within this formulation, and consequently, response bias has been the subject of various reviews (Dusoir, 1975; Macmillan & Creelman, 1990, 1991). In these reviews, competing bias measures were held to a variety of desirable standards. Although Dusoir's earlier review came to no resolutions as to which bias measure was preferable, the re-

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Reprints are available from Brent Alsop at Department of Psychology, University of Otago, P.O. Box 56, Dunedin, New Zealand.

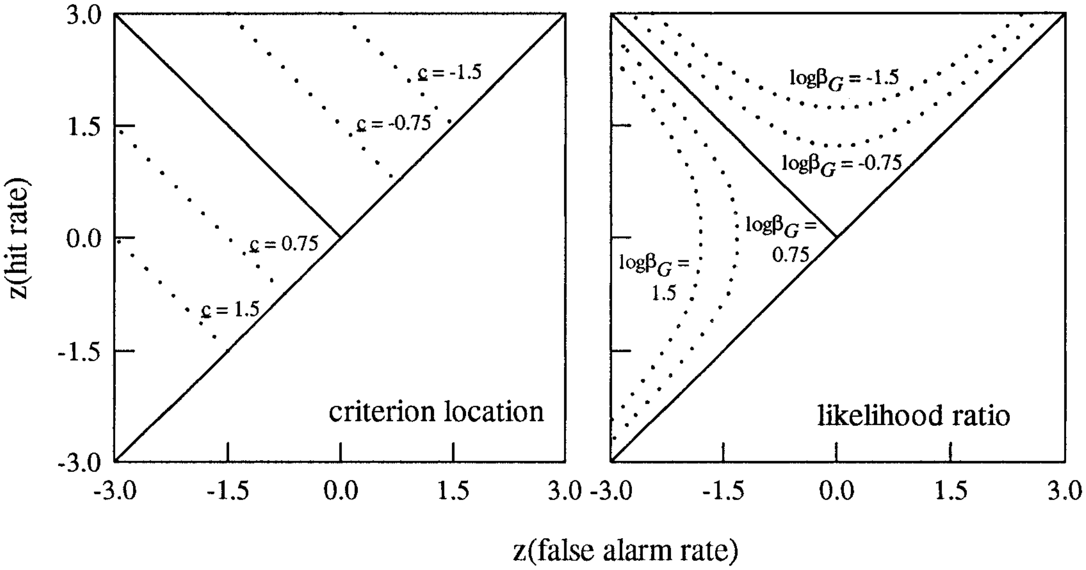

Fig. 1. Isobias functions predicted by the criterion location measure of bias (*c*, left panel) and the likelihood ratio measure of bias (log B_G, right panel). The minor diagonal represents zero bias.

cent reviews favored criterion location measures of bias [e.g., *c*, Green & Swets, 1966; log (*b*), Luce, 1963] rather than more traditional likelihood ratio measures (e.g., log β_G, Green & Swets, 1966; log β_L, Luce, 1963) on theoretical grounds (e.g., criterion location measures preclude meaningful values at below-chance performance). Criterion location measures index bias by measuring the distance between the decision criterion and the intersection of the two stimulus distributions. Likelihood ratio measures index bias by measuring the relative height of the two distributions at the decision criterion. Despite the theoretical support for criterion location measures, there is no consensus as to which measure (or family of measures) is preferable within the psychophysical detection literature. This lack of consensus appears to have arisen because no clear empirical evidence supports the predictions of one measure over the other (Dusoir, 1975; Macmillan & Creelman, 1990, 1991).

The lack of empirical support favoring one family of bias measures is surprising, because the isobias functions predicted by criterion location measures clearly differ from those predicted by likelihood ratio measures. Isobias functions are theoretical points of equal bias across changes in discriminability and can be traced out in what is known as receiver operating charateristic (ROC) space. ROC space plots the hit rate (number of hits divided by the total number of responses on S_1 trials) against the false alarm rate (number of false alarms divided by the total number of responses on S_2 trials). Therefore, isobias functions plot the combinations of hit and false alarm rates that yield the same numerical value for a particular measure of bias. Figure 1 plots the isobias predictions made by a criterion location bias measure, *c*, and those made by a likelihood ratio measure, log β_G. A convenient way to plot isobias functions in ROC space is to plot the false alarm and hit rates as *z* transforms (the inverse of the normal distribution). The advantage of this transformation is that the isobias predictions made by criterion location measures become more linear, and are easier to distinguish from the predictions of other bias measures. As illustrated, constant values of the criterion location bias measure *c* over changes in discriminability are represented by points that are parallel to the minor diagonal. In contrast, constant values of the likelihood ratio bias measure log β_G fan out to the upper right and lower left corners of the ROC space. The functions shown for these two measures are virtually indistinguishable from the isobias predictions made by other criterion location and likelihood ratio measures [e.g., log (*b*) and log β_L bias measures; Luce, 1963]. It appears that a simple detection experiment should produce empirical support for one family of measures over the other; that is, if response bias was held constant over varying levels of discriminability, the resulting isobias function should indicate one family of measures only. Indeed, this type of approach has been used to evaluate competing discriminability measures (Swets, 1986a, 1986b).

Few studies of humans have taken this empirical approach to compare bias measures, and none have indicated any obvious solutions. The one major study of this type compared the shape of bias functions across two different bias-inducing procedures in an auditory detection task (Dusoir, 1983). In the first procedure, the signal presentation ratio was held at 1:1; that is, S_1 and S_2 were presented equally often. Correct left-key responses and correct right-key responses were rewarded with unequal magnitudes of money. In addition, unequal magnitudes of money were deducted for incorrect left-key responses and incorrect right-key responses. In the second procedure, the stimulus presentation ratio was either held at 1:3 or 3:1; that is, S_1 was presented on 25% or 75% of all trials. Equal magnitudes of money were arranged for correct left-key and correct right-key responses, and equal magnitudes of money were deducted for the two types of incorrect responses. The obtained patterns of bias varied widely across individuals and across procedures, with no obvious relation to either the arranged stimulus presentation ratio or the associated reward. Consequently, no single bias measure accurately predicted each subject's performance. Dusoir concluded that different subjects produced different bias functions under presumably identical situations, and questioned the search for a universal bias measure. This type of result led Macmillan and Creelman (1990, 1991) to suggest that uncontrolled cognitive factors were responsible for the inconsistency in human empirical isobias functions. For example, they contended that response bias is influenced by the subject's understanding of the instructions used to produce response bias.

The human psychophysical literature, however, has largely overlooked research that stems from the behavioral models of signal detection (e.g., Alsop & Davison, 1991; Davison & Jones, 1995; Davison & Tustin, 1978; Nevin, Jenkins, Whittaker, & Yarensky, 1982). These models emerged from operant research on nonhuman animal (hereafter, animal) choice and have a different conceptualization of response bias compared to the psychophysical approach. The behavioral approach has focused on animal performance; consequently, experimenters have been forced to examine carefully which features of a task affect behavior. Therefore, a major contribution of behavioral signal-detection research has been to investigate quantitatively the factors that control response bias.

The animal research has shown that the obtained reinforcer ratio (the relative number of reinforcers obtained for correct B_1 vs. correct B_2 responses), rather than the stimulus presentation ratio (the relative number of S_1 to S_2 stimulus presentations), is important in the control of response bias. McCarthy and Davison (1979) recognized that procedures that vary the stimulus presentation ratio to produce response bias also tend to covary the obtained reinforcer ratio by rewarding every correct response (e.g., Bross, 1979; Bross & Sauerwein, 1980; Craig, 1976; Creelman, 1965; Dusoir, 1975; Gescheider, 1974; Healy & Jones, 1975; Mar, Smith, & Sarter, 1996). Asymmetrical reinforcer ratios occur in such procedures because subjects receive more reinforcers associated with the stimulus presented most often, simply because they have more opportunities to do so compared with the less frequently presented stimulus. McCarthy and Davison (1979) report that when the stimulus presentation ratio was varied alone, without the reinforcer ratio covarying, pigeons showed no systematic bias for the key associated with the more frequently presented stimulus. They concluded that effective bias manipulations rely on changes in the reinforcer ratio.

Animal research has also recognized that procedures that vary the stimulus presentation ratio and allow the reinforcer ratio to covary do not necessarily keep the obtained reinforcer ratio constant over changes in discriminability (termed *uncontrolled* reinforcer procedures; e.g., McCarthy & Davison, 1984). If a subject develops a response bias for the more frequently presented (and more frequently rewarded) alternative, proportionately more reinforcers will accrue from that source than arranged. This unequal payoff ratio feeds back to the subject's performance, producing a more extreme response bias and an even more extreme obtained reinforcer ratio. Consequently, the obtained reinforcer ratio can differ radically from the original arranged stimulus presentation ratio. The difference between the obtained and arranged reinforcer ratios will be exacerbated when the two stimuli are difficult to discriminate because subjects will tend to make more errors in this situation. Therefore, uncontrolled reinforcer procedures will tend to produce more extreme reinforcer ratios at low compared to high discriminability. Given that changes in the reinforcer ratio alone produce reliable and systematic changes in response bias in pigeons (e.g., Johnstone & Alsop, 1999; McCarthy & Davison, 1979), bias might vary systematically across changes in stimulus disparity when uncontrolled reinforcer procedures are used.

McCarthy and Davison (1984) examined the ROC functions obtained when reinforcer ratios were arranged using uncontrolled procedures. Pigeons were trained to detect luminance differences between two intensities of light. Five different levels of stimulus disparity were arranged. In the lowest discriminability condition, there was no luminance difference between S_1 and S_2. This stimulus arrangement allowed McCarthy and Davison to examine the effects of the reinforcer ratio in the absence of any stimulus control. Various reinforcer ratios were arranged by varying the stimulus presentation ratio across three levels (1:4, 1:1, and 4:1) at each stimulus disparity and rewarding on average every third correct response. Figure 2A shows that the ROC function obtained from the uncontrolled procedure was most consistent with the likelihood ratio predictions of isobias. Figure 2B plots the obtained log reinforcer ratio [$\log (R_1/R_2)$] against discriminability for the uncontrolled procedure, where R_1 and R_2 represent the numbers of reinforcers obtained from correct B_1 and correct B_2 responses, respectively. The obtained reinforcer ratio varied as a function of stimulus disparity. As the stimuli became harder to tell apart, the obtained reinforcer ratio became more extreme.

McCarthy and Davison's (1984) results show that procedures in which the stimulus presentation ratio is varied and the reinforcer ratio is allowed to covary do not keep the obtained reinforcer ratio constant over changes in discriminability (Figure 2B). Therefore, given that variations in the reinforcer ratio produce reliable changes in bias, McCarthy and Davison asserted that bias curves created by uncontrolled procedures were not true isobias curves. Meaningful isobias functions can be produced only from procedures that hold the relevant independent variables constant over all levels of stimulus discriminability (McCarthy & Davison, 1979, 1981, 1984). This can be achieved when the stimulus presentation ratio is held constant and asymmetrical reinforcer ratios are arranged by using a schedule that controls for the number of reinforcers received for each response alternative. Simply manipulating the probability of reward associated with each type of correct response does not guarantee control of the relative number of reinforcers, even when the stimulus presentation ratio is held constant. For example, a schedule arrangement that rewards .25 of correct B_1 responses and .5 correct B_2 responses does not necessarily mean the subject will receive a 1:2 ratio of B_1 to B_2 reinforcers. Control of the obtained reinforcer ratio can be achieved only when a subject's performance cannot influence the ratio of reinforcement actually received. A schedule arrangement that allows this independence was described by McCarthy and Davison (1984). A computer arranged a reinforcer and specifically designated it to either a correct left- or right-key response according to a prearranged reinforcer ratio. This available reinforcer had to be taken for that particular correct response before another reinforcer was arranged. This forced the ratio of reinforcers received to equal the reinforcer ratio that was arranged. McCarthy and Davison (1984) called this type of reinforcer procedure *controlled*.

Figure 2C shows the ROC functions obtained when reinforcer ratios were arranged using a controlled procedure (McCarthy & Davison, 1984). The stimulus presentation ratio was held constant at 1:1, and, at the five different levels of stimulus disparity, the reinforcer ratio was varied across three conditions (1:4, 1:1, and 4:1) in the manner described above. The resulting ROC functions

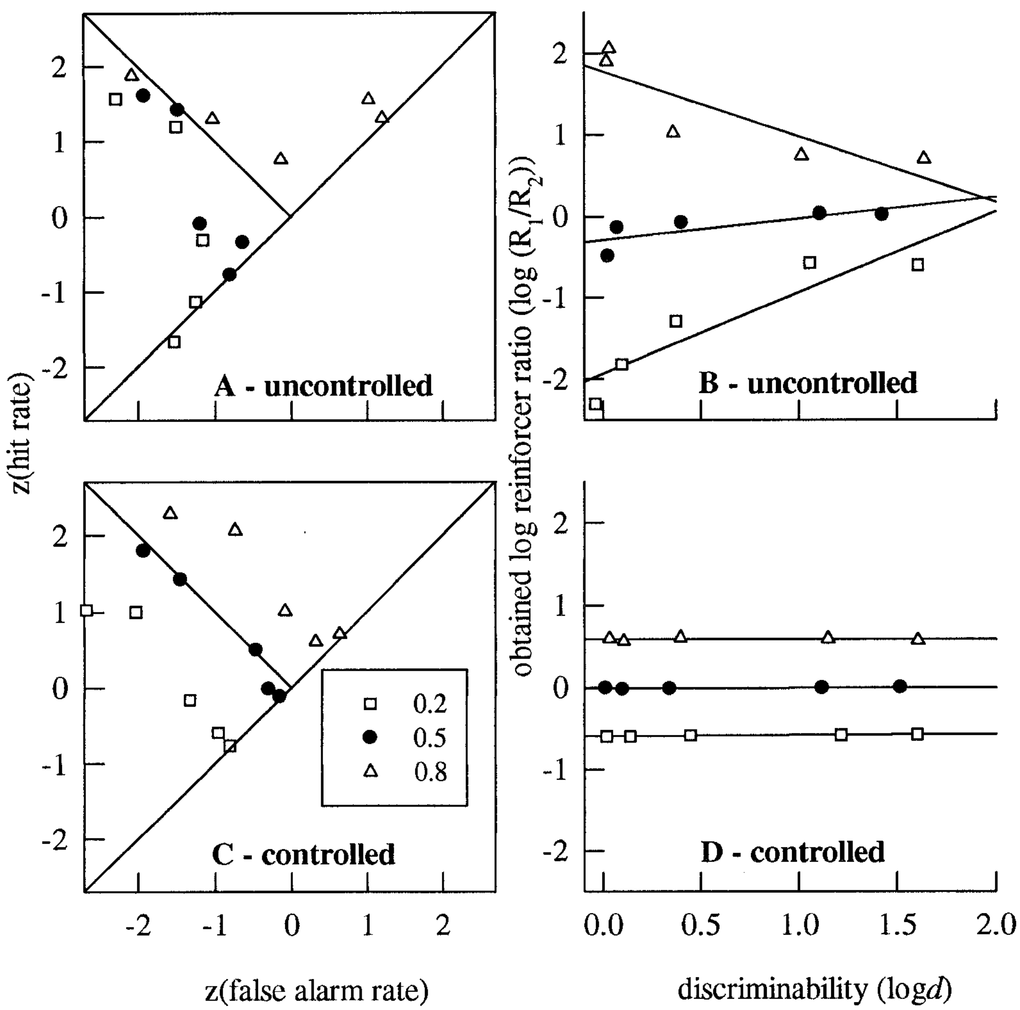

Fig. 2. ROC functions obtained from uncontrolled (Panel A) and controlled (Panel C) payoff procedures over three arranged stimulus presentation ratios (Panel A) and reinforcer ratios (Panel C) using pigeon subjects (McCarthy & Davison, 1984). The corresponding obtained reinforcer ratios are plotted in Panels B and D.

were consistent with the isobias functions predicted by criterion location measures of bias under isobias conditions (Figure 2C). Figure 2D shows that, as expected, the obtained reinforcer ratio [log (R_1/R_2)] remained constant across all levels of stimulus disparity in the controlled procedure.

McCarthy and Davison's (1979, 1981, 1984) research indicates that adequate control of the reinforcer ratio provides the isobias functions to evaluate competing bias measures. The shape of the isobias function predicted by a criterion location measure of bias was more consistent with the obtained empirical bias function when the source of bias was held constant across the different levels of discriminability (McCarthy & Davison, 1984). This empirical work with pigeons complements the theoretical and pragmatic position concerning response bias taken by Macmillan and Creelman (1990, 1991); that is, a criterion location measure of response bias seems preferable to other response bias measures. Despite the implications for investigations into the sources and measurement of human response bias, these animal findings and the associated behavioral models are absent in the more recent reviews of response bias by psychophysical detection researchers (e.g., Macmillan & Creelman, 1991, 1996). This is surprising, because there is a direct quantitative link between the most widely used behavioral model of signal detection (Davison & Tustin, 1978) and choice theory (Luce, 1963). These two models produce equivalent discriminability measures (e.g., log α, Luce, 1963; log *d,* Davison & Tustin, 1978) and bias measures [e.g., log (*b*), Luce, 1963; log *b,* Davison & Tustin, 1978).[1] Systematic studies with humans that replicate the empirical results from pigeons appear to be required (McCarthy & Davison, 1984). The present study compared human response bias performance when controlled and uncontrolled reinforcer procedures were used to manipulate response bias.

METHOD

Subjects

Eight university students were recruited by advertising on local student notice boards. Each subject received $30 payment for their participation. Their ages ranged from 19 to 24 years. Subjects were randomly assigned to either Group 1 (IM, SRP, PV, and JMD) or Group 2 (PVK, AEC, SJR, and AM).

Apparatus

An experimental area (approximately 1 m by 2 m) was created in the corner of a quiet, dimly lit room. This area was curtained off from the rest of the room to minimize visual distractions. The subject sat facing an IBM™-compatible computer, with his or her head approximately 1 m from the monitor. A bar at chest height prevented the subject from leaning closer to the computer.

The computer presented the instructions and the signal-detection task, and recorded subjects' responses. Each stimulus was presented against a black screen and consisted of a 12 × 12 array (71 mm by 71 mm), containing 144 elements. Elements were either a white circle, or a black square defined by a white outline. The diameter of each circle and the width of each square measured 5 mm. There was a 1-mm gap between elements in the array. The proportion of circles to squares in the array was varied to create four levels of stimulus disparity. Stimuli with more circle elements were classed as "more circles"; those with more square elements were classed as "more squares." The difference in the number of circles to squares in the array decreased from Stimulus Levels 1 to 4, and it became harder to determine the more frequent element type. At the easiest discriminability level (1), the ratio of circle elements to square elements (or vice versa) was held at 78:66. This ratio decreased to 76:68 for Discriminability Level 2, 74:70 for Discriminability Level 3, and became equal (72:72) for the hardest discriminability level (4). For this level, the computer determined whether a particular trial would constitute an S_1 or S_2 presentation, and responses were evaluated as correct or incorrect accordingly. This stimulus arrangement allowed an estimate of the effects of the reinforcer ratio in the absence of any differential stimulus factors.

The arrangement of circles and squares in the array was randomly determined on each trial, but was constrained to produce the correct number of circles and squares for the required more circles or more squares stimulus (Discriminability Level 1, 2, 3, or 4). Subjects responded via two telegraph keys connected through the computer's games port. The left key was labeled "more squares," and the right key was labeled "more circles."

Procedure

Each subject participated in eight experimental sessions. Each session lasted approximately 30 min. At the beginning of each session, the following instructions were then presented.

> You will see PATTERNS with either more squares [an example array showing more squares was presented] or more circles [an example array showing more circles was presented]. You will only see ONE pattern at a time. If there are more SQUARES, press the LEFT button. If there are more CIRCLES press the RIGHT button. Each pattern appears for 2 seconds. A small + precedes each trial—Like this. [The small cross was then presented, followed by the presentation of a more squares array.] That pattern had more squares

[1] Although the theoretical underpinnings of log (*b*) and log *b* are conceptually different, these two measures are indexed equivalently and make the same predictions in ROC space (see Davison & Tustin, 1978). Therefore, log *b* can be regarded as belonging to the family of criterion location bias measures.

> so press the LEFT key. Sometimes you are told you are correct and you win a point. This looks like [The words ''Correct'' and ''You win a point!'' were then displayed in the center of the screen against a colored pattern of pixel ''stars'' and a brief presentation of a 1000-Hz tone.] Sometimes you are told nothing. You could be right or wrong. Get as many points as possible. [The final instruction screen was then presented.] Are you ready to begin the experiment? Remember: Press the left key if there are more squares, and right key if there are more circles. Press any key to begin.

Five hundred experimental trials then began. Each trial began with a yellow cross presented in the middle of the screen for 750 ms. This cross served as a fixation point and a warning signal. An array stimulus then appeared. The array remained on the screen until the subject responded, or for a maximum of 2 s. If no response was made within the 2-s period, the screen went blank and remained blank until the subject made a choice. If the subject made a correct choice, a reinforcer was presented only if one was scheduled for that type of response. The screen remained blank in all other cases (incorrect responses and correct but nonreinforced responses). The total amount of time elapsed between the response and the next trial was 1,250 ms in reinforced and nonreinforced trials. Each session was divided into five blocks of 100 trials. t the end of each block, the total number of points earned by the subject was displayed on the screen. Subjects could take a small break from the task and began the next block by pressing any key.

A controlled reinforcer procedure was arranged for four experimental sessions. The type of stimulus on a trial was selected randomly with equal probability; that is, the numbers of S_1 and S_2 trials were equal. The asymmetrical reinforcer ratios were achieved using a controlled reinforcer procedure (McCarthy & Davison, 1979) that fixed the reinforcer ratio for correct responses. The computer selected the next correct response to receive a point (either a correct more circles or more squares response). This available point had to be received before the computer selected the next type of correct response to receive a point. This ensured that the reinforcer ratio obtained would equal that arranged.

One potential confounding effect was that subjects might receive a greater overall reinforcement rate for high-discriminability conditions than for low-discriminability conditions (simply because subjects are correct more frequently at high discriminability levels). Therefore, how often a reward was made available for a correct response was also partially controlled over changes in discriminability. As discriminability increased, the availability of a reward for correct responses was decreased. This decrease was achieved by the addition of null consequences, which the computer could also select in increasing numbers as discriminability increased. If the computer selected a null consequence, the next correct response from either key received no reinforcer.

One discriminability level (1, 2, 3, or 4) was presented per session. Each group of subjects received one of two possible reinforcer conditions. Group 1 received four times as many points per session for correct more circles (right-key) responses than for correct more squares (left-key) responses for all four sessions (Conditions $1_{1:4}$, $2_{1:4}$, $3_{1:4}$, and $4_{1:4}$, Stimulus Levels 1, 2, 3, and 4, respectively). Group 2 received four times as many points per session for correct more squares (left-key) responses than for more circles (right-key) responses for all four sessions (Conditions $1_{4:1}$, $2_{4:1}$, $3_{4:1}$, and $4_{4:1}$, Stimulus Levels 1, 2, 3, and 4, respectively).

In the remaining four sessions, asymmetrical reinforcer ratios were arranged using an uncontrolled reinforcer procedure (McCarthy & Davison, 1979). Points were available on a single variable-ratio (VR) 3 schedule. This meant that on average, every third correct response produced a point regardless of whether it was a left-key or right-key response. The VR 3 schedule was chosen (rather than a VR 4 or VR 5, for example) so that the overall reinforcement rate obtained in the uncontrolled procedure approximated that obtained in the controlled procedure. The relative frequency of reinforcers for the two correct responses (more circles and more squares) was varied by altering the presentation ratio of the more circles and more squares stimuli within each session. For Group 1, the stimulus presentation ratio was held at 4:1 for all four sessions (Conditions $5_{4:1}$, $6_{4:1}$, $7_{4:1}$, and $8_{4:1}$, Stimulus Levels 1, 2,

Table 1

The presentation order of each condition for each subject. A controlled reinforcer procedure was used to produce the reinforcer ratios for Conditions 1, 2, 3, and 4. The subscripts for these conditions indicate the ratio of left to right key reinforcers. An uncontrolled reinforcer procedure was used to produce the reinforcer ratio for Conditions 5, 6, 7, and 8. The subscripts for these conditions indicate the presentation ratio of S_1 to S_2 trials.

Subject	1st	2nd	3rd	4th	5th	6th	7th	8th
IM	$1_{1:4}$	$4_{1:4}$	$2_{1:4}$	$3_{1:4}$	$5_{4:1}$	$8_{4:1}$	$6_{4:1}$	$7_{4:1}$
SRP	$5_{4:1}$	$8_{4:1}$	$6_{4:1}$	$7_{4:1}$	$1_{1:4}$	$4_{1:4}$	$2_{1:4}$	$3_{1:4}$
PV	$3_{1:4}$	$2_{1:4}$	$4_{1:4}$	$1_{1:4}$	$7_{4:1}$	$6_{4:1}$	$8_{4:1}$	$5_{4:1}$
JMD	$7_{4:1}$	$6_{4:1}$	$8_{4:1}$	$5_{4:1}$	$3_{1:4}$	$2_{1:4}$	$4_{1:4}$	$1_{1:4}$
PVK	$1_{4:1}$	$4_{4:1}$	$2_{4:1}$	$3_{4:1}$	$5_{1:4}$	$8_{1:4}$	$6_{1:4}$	$7_{1:4}$
AEC	$5_{1:4}$	$8_{1:4}$	$6_{1:4}$	$7_{1:4}$	$1_{4:1}$	$4_{4:1}$	$2_{4:1}$	$3_{4:1}$
SJR	$3_{4:1}$	$2_{4:1}$	$4_{4:1}$	$1_{4:1}$	$7_{1:4}$	$6_{1:4}$	$8_{1:4}$	$5_{1:4}$
AM	$7_{1:4}$	$6_{1:4}$	$8_{1:4}$	$5_{1:4}$	$3_{4:1}$	$2_{4:1}$	$4_{4:1}$	$1_{4:1}$

3, and 4, respectively). This meant that S_1 (more squares) was presented on 80% of the trials. For Group 2, the stimulus presentation ratio was held at 1:4 for all four sessions (Conditions $5_{1:4}$, $6_{1:4}$, $7_{1:4}$, and $8_{1:4}$, Stimulus Levels 1, 2, 3, and 4, respectively). This meant that S_1 (more squares) was presented on 20% of the trials.

The order of the eight sessions was partially counterbalanced over the 8 subjects, with the constraint that the controlled and uncontrolled sessions were run consecutively. Table 1 contains the presentation order for each subject.

RESULTS

The last 300 trials from each condition were analyzed separately for each subject. The numbers of B_1 and B_2 responses on S_1 trials (B_{11} and B_{12}) and on S_2 trials (B_{21} and B_{22}) were calculated for each session for each subject. The number of reinforcers obtained for each type of correct response was also calculated for each session (R_1 and R_2, respectively). Corresponding measures of discriminability (log d) and response bias (log b) were also calculated (see Davison & Tustin, 1978). These values are given in Table 2. The hit rate $[H = B_{11}/(B_{11} + B_{12})]$ and the false alarm rate $[F = B_{21}/(B_{21} + B_{22})]$ were also calculated for each session for each subject and were converted into z scores.

Figure 3A plots the $z(H)$ versus the $z(F)$ for each subject in each condition for the controlled procedure. Group 1 subjects received the 1:4 reinforcer ratio in the controlled procedure, and their data are orderly and show a high degree of similarity across subjects. Overall, these points trace out functions that are parallel to the minor diagonal and are most consistent with log b and criterion location isobias functions (see Figure 1). The only exceptions are the two data points obtained from Subject JMD (marked with arrows). Group 2 subjects received the 4:1 reinforcer ratio in the controlled procedure (Figure 3A). Although the relations were more variable across subjects, the roughly linear relations were again more consistent with log b and criterion location isobias functions. The data points obtained from Subjects AM and AEC show departures from this general pattern at high discriminabilities, but the differences are not systematic. The only major outlier was one data point obtained from Subject PVK (marked with an arrow).

The outlying points in Figure 3A (marked with arrows) probably resulted from an order effect. The outlier from PVK was from the fifth session, and the outliers from JMD were obtained from the fifth and sixth sessions; these were the sessions immediately following the change in procedure and the reversal of the reinforcer ratio. For these subjects it seems likely that bias carried over from the reinforcer ratio arranged in the previous four sessions.

Figure 3B plots the corresponding points from the uncontrolled procedure. In general, these points are more scattered and show less similarity across subjects than those points obtained from the controlled procedure. Group 1 subjects received a stimulus presentation ratio of 4:1. These points tended to fan out to the top right corner as stimulus disparity decreased. Group 2 subjects received a stimulus presentation ratio of 1:4. Their points tended to fan out towards the bottom left corner as stimulus disparity decreased. The overall pattern of bias obtained from all subjects was variable, and the obtained ROC points did not seem to be consistent with the isobias predictions made by either the likelihood ratio or the log b measures of bias. Although the patterns of bias were more similar to the likelihood ratio predictions, they did not match directly, because most subjects failed to reach the lower left or upper right corners of the

ROC space at very low discriminabilities. There were some outliers obtained from the uncontrolled procedure. These are marked by arrows in Figure 3B (Subjects AM and AEC). Again, these points were from the fifth session (Subjects AM and AEC) and the sixth session (the remaining point for Subject AEC).

The two different procedures (controlled and uncontrolled) produced different patterns of bias. When the asymmetrical reinforcer ratio was held constant across changes in stimulus disparity, resulting ROC plots resembled the linear isobias functions predicted by a log *b* or criterion location measure of bias. The same subjects produced functions that were variable and fanned out from the minor diagonal when the asymmetrical reinforcer ratio was produced by an uncontrolled procedure. Although the overall patterns shown in Figure 3 favor a criterion location bias measure, a more direct test is required. This is provided by comparing the corresponding log *b* for each subject in each condition with log *d*. Figure 4A plots the log *b* measures obtained for each subject across changes in discriminability in the controlled procedure. In general, the data obtained in the controlled procedure were orderly, and there was no evidence to suggest a log *b* measure of bias changed systematically as a function of discriminability. A regression analysis on the data from the subjects in the 1:4 reinforcer condition showed that the slope was not significantly different from zero: slope = −0.40, SE = 0.26, $F(1, 14) = 2.29$, $p > .05$. Likewise, the slope associated with the subjects from the 4:1 reinforcer ratio was also not significantly different from zero: slope = 0.33, SE = 0.26, $F(1, 14) = 1.60$, $p > .05$.

Figure 4B plots the log *b* measures obtained for each subject across conditions in the uncontrolled procedure. In general, these points were less orderly than those in Panel A. As stimulus disparity increased, log *b* bias measures approached zero. A significant positive relation was found for subjects in the 1:4 reinforcer ratio [slope = 0.73, SE = 0.19, $F(1, 14) = 14.30$, $p \leq .05$], whereas a significant negative relation was found for subjects in the 4:1 reinforcer ratio [slope = −0.89, SE = 0.39, $F(1, 14) = 5.13$, $p \leq .05$]. That is, log *b* became less extreme as discriminability increased for all subjects in the uncontrolled procedure.

Why did the log *b* measure change as a function of discriminability when the uncontrolled procedure was used? McCarthy and Davison (1984) found that the difference between the results obtained for the controlled and uncontrolled procedures was correlated with systematic changes in the ratio of obtained reinforcers as discriminability varied. The same result was found here. Figure 5 examines changes in the obtained reinforcer ratio as a function of changes in stimulus disparity. The logarithm of the left-key (R_1) to right-key (R_2) reinforcers is plotted against discriminability for each subject in each condition. The controlled reinforcer procedure should ensure a constant reinforcer ratio over all levels of stimulus disparity. Figure 5A shows that this was achieved. Regression analyses for the 1:4 reinforcer conditions [slope = −0.04, SE = −0.04, $F(1, 14) = 2.05$, $p > .05$] and the 4:1 conditions [slope = 0.01, SE = 0.02, $F(1, 14) = 0.54$, $p > .05$] showed no evidence that log (R_1/R_2) changed systematically as a function of discriminability. Unlike the controlled reinforcer procedure, the uncontrolled procedure produced systematic changes in the reinforcer ratio as a function of discriminability (Figure 5B). The reinforcer ratio tended to become more extreme as discriminability decreased. This is shown by a significant positive relation for subjects in the conditions in which the stimulus presentation ratio was held at 1:4 [slope = 0.40, SE = 0.15, $F(1, 14) = 6.72$, $p \leq .05$] and a significant negative relation for subjects in the conditions in which the stimulus presentation ratio was held at 4:1 [slope = −1.13, SE = 0.30, $F(1, 14) = 14.16$, $p \leq .05$]. Only at the highest discriminabilities did subjects receive the reinforcer ratio that was like that arranged by the stimulus presentation ratio. Note that the fitted regression lines in Figures 4 and 5 are not meant to imply a strict linear relation between log *b* and discriminability, or between the obtained reinforcer ratio and discriminability. Instead, they are a convenient way to illustrate that changes in discriminability are accompanied by systematic changes in response bias and the reinforcer ratio in the uncontrolled procedure but not in the controlled procedure.

A comparison of Figures 4 and 5 shows that

Table 2

The number of B_{11}, B_{12}, B_{21}, and B_{22} responses and R_1 and R_2 reinforcers are shown for each subject in each condition. Corresponding values of log d and log b have also been calculated.

Subject	Condition	B_{11}	B_{12}	B_{21}	B_{22}	R_1	R_2	log d	log b
IM	$1_{1:4}$	98	52	14	136	21	84	0.63	−0.36
	$2_{1:4}$	76	74	33	117	21	78	0.28	−0.27
	$3_{1:4}$	63	87	31	119	21	79	0.22	−0.36
	$4_{1:4}$	49	101	50	99	18	73	−0.01	−0.31
	$5_{4:1}$	203	37	6	54	101	30	0.85	−0.11
	$6_{4:1}$	194	46	16	44	97	17	0.53	0.09
	$7_{4:1}$	181	59	33	27	91	17	0.20	0.29
	$8_{4:1}$	158	82	43	17	74	9	−0.06	0.34
SRP	$1_{1:4}$	89	61	16	134	19	75	0.54	−0.38
	$2_{1:4}$	50	100	23	126	19	72	0.22	−0.52
	$3_{1:4}$	50	97	32	113	21	77	0.13	−0.42
	$4_{1:4}$	45	104	48	101	18	69	−0.02	−0.34
	$5_{4:1}$	205	34	14	46	110	27	0.65	0.13
	$6_{4:1}$	225	10	40	20	113	8	0.53	0.83
	$7_{4:1}$	192	40	46	13	85	6	0.07	0.62
	$8_{4:1}$	165	32	35	12	83	4	0.12	0.59
PV	$1_{1:4}$	83	67	12	137	21	81	0.58	−0.48
	$2_{1:4}$	57	92	22	127	19	78	0.28	−0.48
	$3_{1:4}$	50	99	36	114	18	70	0.10	−0.40
	$4_{1:4}$	19	59	17	59	12	40	0.02	−0.52
	$5_{4:1}$	141	54	15	33	77	15	0.38	0.04
	$6_{4:1}$	108	12	17	11	58	8	0.38	0.57
	$7_{4:1}$	109	20	22	6	63	2	0.09	0.65
	$8_{4:1}$	109	15	22	1	56	1	−0.24	1.10
JMD	$1_{1:4}$	68	73	24	113	17	71	0.32	−0.35
	$2_{1:4}$	66	81	34	110	14	51	0.21	−0.30
	$3_{1:4}$	92	42	96	40	2	8	−0.02	0.36
	$4_{1:4}$	73	56	64	62	16	57	0.05	0.06
	$5_{4:1}$	228	12	24	36	101	19	0.73	0.55
	$6_{4:1}$	233	1	58	1	128	1	0.30	2.07
	$7_{4:1}$	225	11	57	1	99	1	−0.22	1.53
	$8_{4:1}$	198	19	52	3	101	1	−0.11	1.13
PVK	$1_{4:1}$	84	66	23	127	64	15	0.42	−0.32
	$2_{4:1}$	119	31	64	86	84	20	0.36	0.23
	$3_{4:1}$	97	53	69	81	79	19	0.17	0.10
	$4_{4:1}$	102	48	106	44	64	16	−0.03	0.35
	$5_{1:4}$	42	18	36	203	25	96	0.56	−0.19
	$6_{1:4}$	33	26	57	182	14	86	0.30	−0.20
	$7_{1:4}$	14	46	35	205	5	107	0.13	−0.64
	$8_{1:4}$	20	40	75	165	7	86	0.02	−0.32
AEC	$1_{4:1}$	147	1	104	46	64	17	0.91	1.26
	$2_{4:1}$	144	6	74	76	89	23	0.70	0.68
	$3_{4:1}$	137	13	105	45	83	21	0.33	0.70
	$4_{4:1}$	122	28	118	32	62	17	0.04	0.60
	$5_{1:4}$	59	1	62	178	25	98	1.11	0.66
	$6_{1:4}$	49	11	40	200	25	100	0.67	−0.03
	$7_{1:4}$	36	24	59	181	19	94	0.33	−0.16
	$8_{1:4}$	36	24	132	107	19	49	0.04	0.13
SJR	$1_{4:1}$	146	4	37	113	93	23	1.02	0.54
	$2_{4:1}$	133	16	68	82	82	22	0.50	0.42
	$3_{4:1}$	125	23	78	71	86	21	0.35	0.39
	$4_{4:1}$	107	38	98	49	65	18	0.07	0.38
	$5_{1:4}$	59	1	40	200	28	100	1.24	0.54
	$6_{1:4}$	31	28	34	206	12	103	0.41	−0.37
	$7_{1:4}$	26	34	33	207	16	102	0.34	−0.46
	$8_{1:4}$	8	51	31	208	6	100	0.01	−0.82

Table 2

(*Continued*)

Subject	Condition	B_{11}	B_{12}	B_{21}	B_{22}	R_1	R_2	log d	log b
AM	$1_{4:1}$	140	10	39	111	92	22	0.80	0.35
	$2_{4:1}$	144	6	84	66	87	21	0.64	0.74
	$3_{4:1}$	134	16	99	51	68	17	0.32	0.61
	$4_{4:1}$	122	28	123	27	53	13	−0.01	0.65
	$5_{1:4}$	43	17	17	223	25	102	0.76	−0.36
	$6_{1:4}$	38	22	39	200	16	101	0.47	−0.24
	$7_{1:4}$	39	21	100	140	18	73	0.21	0.06
	$8_{1:4}$	14	46	63	177	8	98	−0.03	−0.48

the log b measure of bias was highly related to the obtained reinforcer ratio. When the reinforcer ratio remained constant over changes in discriminability in the controlled procedure, log b also remained stable. When the reinforcer ratio became less extreme as discriminability increased in the uncontrolled procedure, log b also became less extreme. This relation between log b and the obtained reinforcer ratio provides a possible explanation for the pattern of results found in the uncontrolled procedure (Figure 3B).

A similar analysis using the likelihood ratio measure was also conducted. Likelihood ratio measures changed systematically with discriminability in the controlled procedure, a finding that was expected from the shape of the ROC functions obtained from this procedure. How well did the likelihood ratio measure account for isobias in the uncontrolled procedure? Figure 6 plots the likelihood ratio bias obtained from the uncontrolled procedure against discriminability (log d). The points are scattered, and there is a large amount of

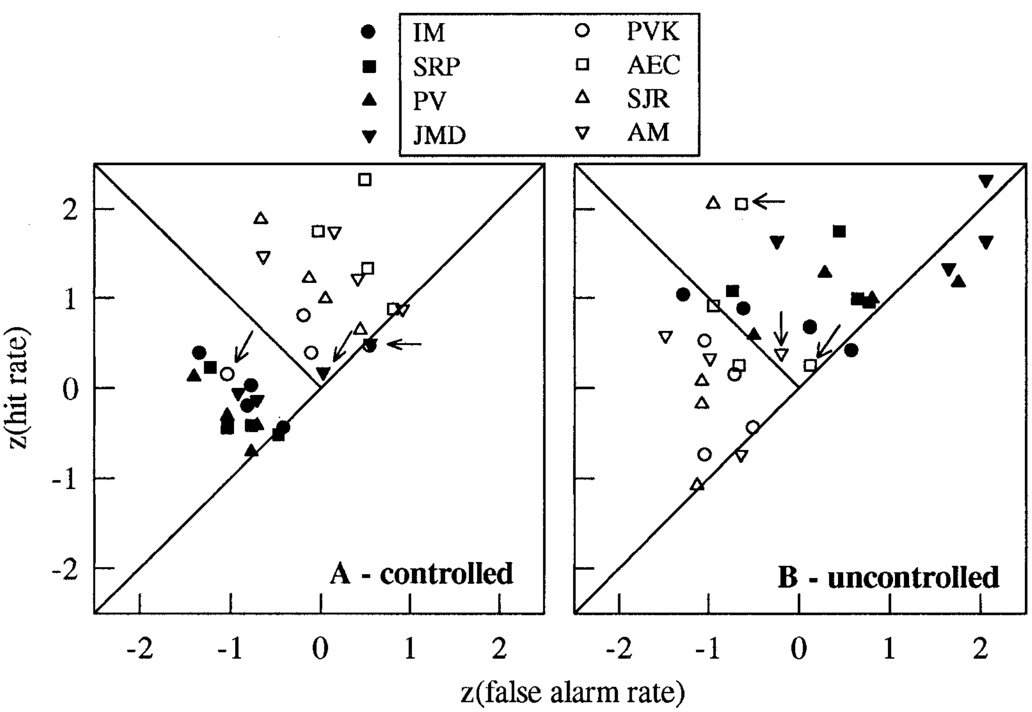

Fig. 3. ROC functions obtained from controlled (Panel A) and uncontrolled (Panel B) reinforcer procedures using human subjects. The symbol type associated with each subject (shown in the legend) is also used for Figures 4, 5, and 6.

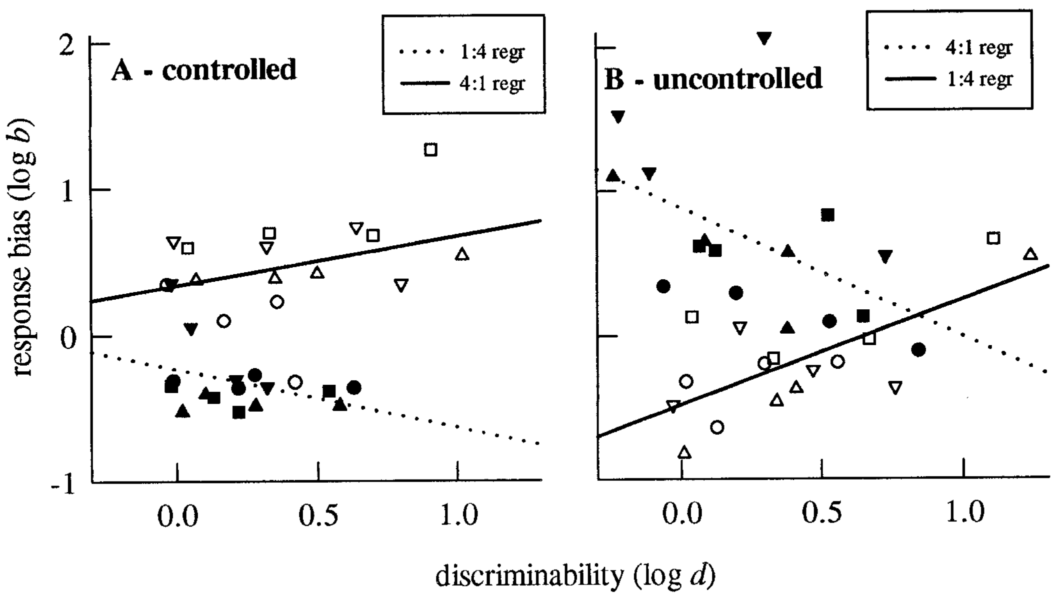

Fig. 4. Response bias as indexed by log *b* (see Davison & Tustin, 1978) plotted over changes in discriminability for the controlled (Panel A) and the uncontrolled (Panel B) reinforcer procedures.

intersubject variability as discriminability increased. In general, likelihood bias measures decreased as discriminability increased. This is shown by significant negative relations for both the 1:4 reinforcer ratio [slope = −1.11, SE = 0.43, $F(1, 14) = 6.63$, $p \leq .05$] and the 4:1 reinforcer ratio [slope = −1.17, SE = 0.40, $F(1, 14) = 8.80$, $p \leq .05$]. Thus, although the ROC points obtained from the uncontrolled procedure follow a general pattern similar to likelihood ratio predictions, this measure did not remain fixed, as an isobias account would require.

DISCUSSION

The bias pattern shown in ROC space depended on the type of reinforcement procedure that was used to generate the bias (Figure 3). Controlled reinforcer procedures produced functions that were more consistent with isobias predictions made by criterion location measures of bias [e.g., *c*, Green & Swets, 1966; log (*b*), Luce, 1963; log *b*, Davison & Tustin, 1978]. Uncontrolled reinforcer procedures produced functions that were somewhat similar to isobias predictions made by likelihood ratio measures of bias (e.g., log β_G, Green & Swets, 1966; log β_L, Luce, 1963). A comparison of the obtained bias measures with the obtained reinforcer ratio suggested that differences in the ROC plots were attributable to differences in the obtained reinforcer ratios.

The ROC functions produced by the human subjects for controlled and uncontrolled reinforcer procedures in the current study (Figure 3) were consistent with those found using pigeons (McCarthy & Davison, 1984). Figure 7 plots the mean human ROC functions for the two reinforcer ratios along with the mean pigeon performance for the equivalent reinforcer ratios. The bias patterns shown by the humans are similar to those shown by the pigeons for both the controlled and the uncontrolled reinforcer procedures. Furthermore, the degree of bias shown by the humans and pigeons was similar when equivalent reinforcer ratios were employed.

It could be argued that when a controlled procedure was used, subjects held criterion location bias constant, and when an uncontrolled procedure was used, subjects held likelihood ratio bias constant. This explanation can be criticized on two grounds. First, although the ROC patterns obtained from the uncontrolled procedure (Figure 3B) were somewhat like the predictions made by the likelihood ratio measure of bias, a likelihood ratio measure of bias did not remain constant

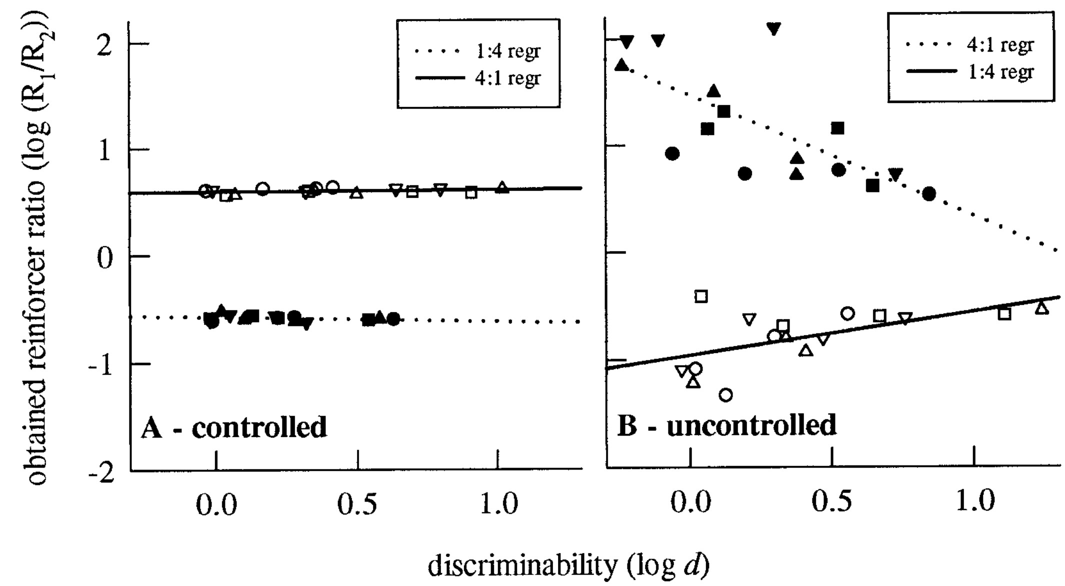

Fig. 5. The obtained reinforcer ratios [log (R_1/R_2)] plotted against discriminability for the controlled (Panel A) and the uncontrolled (Panel B) reinforcer procedures.

across changes in discriminability (Figure 6), and therefore failed to provide an isobias account. Second, it is unclear why subjects would use different indexes of bias for these two procedures. It seems more parsimonious to describe bias in the two procedures as a function of the obtained reinforcer ratio. Under this explanation, the criterion location measure holds in both procedures. When the factors that influence bias (i.e., the reinforcer ratio) were held constant across changes in discriminability in the controlled procedure, criterion location measures remained constant. When the obtained reinforcer ratio varied across changes in discriminability, criterion location measures were not constant. Instead, they covaried with the changes in the reinforcer ratio (Figures 4 and 5).

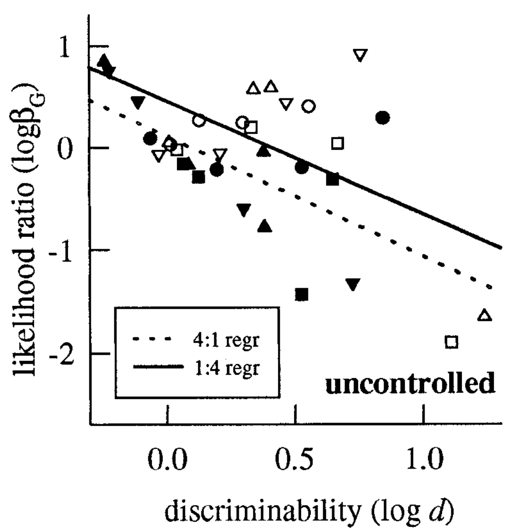

Fig. 6. Likelihood ratio bias plotted against discriminability for the uncontrolled reinforcer procedure.

Response bias in the uncontrolled procedure might have been a function of both the reinforcer ratio and the underlying stimulus presentation ratio. To evaluate whether the stimulus presentation ratio contributed to bias, the log *b* estimates obtained from the uncontrolled procedure were plotted against the obtained reinforcer ratio. A regression analysis was then performed on these data, and the residuals were plotted as a function of the stimulus presentation ratio. Overall, there was no systematic change in the obtained residuals over the two stimulus presentation ratios: slope = -0.14, $SE = 0.09$, $F(1, 30) = 2.21$, $p > .05$. This suggested that the stimulus presentation ratio did not affect response bias. A more detailed residual analysis suggested that an effect of the stimulus presentation ratio on bias might depend on changes in discriminability. Figure 8 shows the residuals from the regession analysis plot-

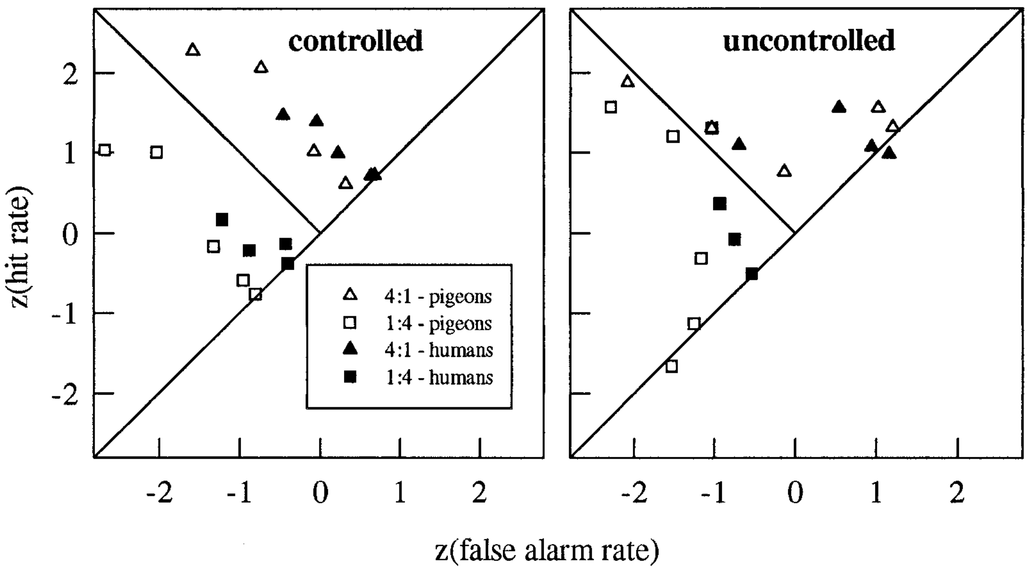

Fig. 7. Human (present study) and pigeon (McCarthy & Davison, 1984) ROC functions obtained from controlled (upper panel) and uncontrolled (lower panel) reinforcer procedures for two arranged reinforcer ratios.

ted separately for each level of discriminability. At the three lower levels of discriminability, the residual plots show no systematic effects of the stimulus presentation ratio. At the highest discriminability level, the residuals associated with the 1:4 stimulus presentation ratio conditions are more positive than those associated with the 4:1 conditions; that is, there is a systematic bias for the key associated with the stimulus presented less often.

The small number of data points per condition shown in Figure 8 precludes any definitive statement regarding the influence of the stimulus presentation ratio in the current experiment, but this pattern of results has precedents in other human detection work. Changes in the stimulus presentation ratio alone also produce these somewhat paradoxical results with human subjects (Alsop, Rowley, & Fon, 1995; Johnstone & Alsop, 1996; Tanner, Haller, & Atkinson, 1967; Tanner, Rauk, & Atkinson, 1970). If the stimulus presentation ratio influences bias, however, this does not change the conclusions of the current experiment. Instead, it provides further evidence that uncontrolled procedures are unsuitable for isobias evaluations.

Overall, this study supports criterion loca-

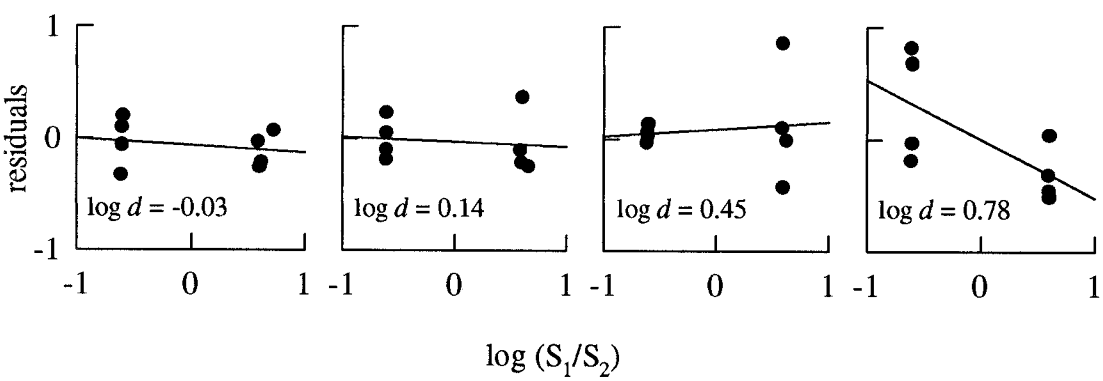

Fig. 8. Residuals (from an analysis that regressed bias against the obtained reinforcer ratios from the uncontrolled procedure) plotted against the obtained stimulus presentation ratio at each of the four levels of discriminability.

tion measures of bias; that is, when the factors that produce bias are held constant across changes in discriminability, ROC functions match the predictions made by criterion location bias measures. These results corroborate Macmillan and Creelman's (1990, 1991) theoretical contention that the criterion location measures are presently the best. These results have implications for both the theory and application of signal detection.

It seems likely that inadequate control of the factors that produce bias has hindered investigations of response bias and its sources (e.g., Dusoir, 1983). Past studies have used uncontrolled reinforcer procedures and, consequently, the obtained reinforcer ratio probably varied across subjects and across levels of discriminability. In addition, past experiments often used complex reinforcer procedures and verbal instructions to produce bias. This creates difficulties relating response bias to any measurable aspect of the experimental situation. For example, Dusoir (1983) arranged positive consequences for correct responses and negative consequences for incorrect responses, varied the stimulus presentation ratio, and gave verbal instructions. In situations such as these, it is unclear which procedural features affect bias. The current experiment emphasizes the need to isolate possible factors in future signal-detection experiments with humans.

This study also has important implications for the use of signal detection in applied settings and in experimental psychology generally. There is a trend towards the use of detection analysis to examine performance on a variety of tasks in which discriminability and response bias are regarded as important dependent variables (e.g., Bross & Borenstein, 1982; Jansen, de Gier, & Slangen, 1985; Koek & Slangen, 1984; Mongrain & Standing, 1989; Wesnes & Warburton, 1983). The present study suggests that some caution is needed when biases are compared. For example, if uncontrolled reinforcer ratios are arranged and discriminability differs between groups, then Figure 3B suggests that a criterion location measure of bias will differ between the two groups (it is less clear what a likelihood ratio measure would show). This bias difference might have resulted from different reinforcer ratios at the two discriminability levels, rather than a true bias difference between the two groups. This problem indicates that bias measures can be meaningfully interpreted only when discriminability between the groups is similar or when some adjustment is made for differences in the obtained reinforcer ratios (e.g., McCarthy, 1991).

The present study successfully brings together research and ideas from animal studies and from contemporary signal-detection research. This approach has related human response bias to a measurable aspect of the experimental situation, the reinforcer ratio, which determined the shape of the resulting ROC functions. This research with human subjects provides empirical support for a criterion location measure of bias and indicates why this measure might vary in some circumstances.

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